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Satellite imagery of the oceans has become an invaluable tool for the oceanographer, adding the breadth of synoptic coverage to the depth of in situ measurements at a few points. But the deluge of oceanographic data expected to come from satellites in the near future will pose severe problems for operational interpreters that will be added to the problems caused by the impracticality of automated image understanding and the uneven quality of human interpretation by different analysts. Expert systems offer a possible way out of the dilemma.

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Development of an Expert System for Interpretation of Oceanographic Images

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Foreword

The deluge of oceanographic data provided by satellites in the near future will pose severe problems for operational interpreters, in addition to the difficulty (or impracticality) of automated interpretation and the uneven quality of human interpretation. Expert systems—computer programs that incorporate a knowledge base and an inference mechanism, and "think" like a human expert—offer a possible way out of the dilemma.

This report describes the early stages of work, sponsored by the Naval Ocean Research and Development Activity, Remote Sensing Branch, to develop such an expert system. This effort is one of the first to apply the concepts of machine intelligence to "image understanding" of natural scenes. In the future, operational Navy facilities may derive great benefit from knowledge-based aids to the interpreter.

R. P. Onorati, Captain, USN
Commanding Officer, NORDA

Executive summary

Satellite imagery of the oceans has become an invaluable tool for the oceanographer, adding the breadth of synoptic coverage to the depth of in situ measurements at a few points. But the deluge of oceanographic data expected to come from satellites in the near future will pose severe problems for operational interpreters that will be added to the problems caused by the impracticality of automated image understanding and the uneven quality of human interpretation by different analysts. Expert systems offer a possible way out of the dilemma.

Current work is directed toward developing and implementing a prototype expert system that ''knows'' about mesoscale ocean features in the Gulf Stream region of the North Atlantic; future development should yield expert systems with other applications. The domain of the prototype expert system is a sequence of registered satellite infrared images. The events represented in the knowledge base are landmass boundaries, warm-core eddies, cold-core eddies, boundaries of the Gulf Stream, and areas on the Gulf Stream boundaries in which locally rapid changes are occurring. The logical/mathematical representation for each type of event includes a set of attributes that range from single numerical values to functions that describe shape. Later versions of the expert system will attempt to use inference rules to fill in information concerning areas obscured by clouds by processing information about events from all images in a sequence. Thus, some of the rules in the knowledge base are an initial attempt to describe the evolution of events.

A major portion of the report consists of a tabulation, in layman's language, of knowledge-base information about warm-core rings, cold-core rings, and the Gulf Stream. The knowledge base includes information on the formation, expected movement, evolution and decay of rings, other ring characteristics and special cases, and general information about the Gulf Stream. Literature citations are provided for each rule. The report also briefly describes a pilot implementation of the expert system and compares several candidate implementation languages.

Acknowledgments

The work described in this report was performed under contract to NORDA's Remote Sensing Branch. Matthew Lybanon was the Scientific Officer. The work was supported by Program Elements 62759N and 63704N.

Contents

Development of an expert system for interpretation of oceanographic images

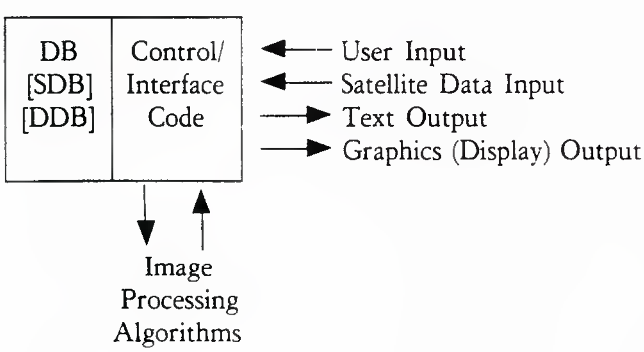
I. Introduction

This report describes the development of a prototype expert system to support the work of the Remote Sensing Branch of the Naval Ocean Research and Development Activity (NORDA) in processing and interpreting satellite data. As indicated from previous research [8,18], this development is one step toward the ultimate goal of implementing a robust system using state-of-the-art techniques in

- image sequence analysis (because a great deal of relevant oceanographic information is sequential in nature and must be extracted from temporal sequences of registered data);
- multisensor integration (because increasing amounts of data will be supplied by a variety of sensors, as planned for the Navy Remote Ocean Sensing System, N-ROSS, in 1990);
- image understanding (because the oceanographic events of interest must be located and their interactions described);
- expert systems (as the most powerful computing methods currently available to model human experts in complex environments).

The current project has concentrated on identifying types of oceanographic events related to important mesoscale features (that is, with length scales roughly 50–300 km) for which study via satellite data is feasible; on acquiring a knowledge base of expertise about these events by contacts with experts at NORDA and by reviewing the technical literature in oceanography; on implementing an embryonic, knowledge-based display of events and their evolution; and on beginning the encoding of more subtle aspects of the knowledge base for future expansion.

The system is being organized generally as follows.



In addition to the Control/Interface procedures, a database (DB) is partitioned into static (SDB) and dynamic (DDB) sections. The SDB contains the full knowledge base which represents contemporary information about and the understanding of oceanographic imagery/sensing, mesoscale events, and event interactions. The DDB is the "working memory," which at any given time contains the current facts about the area under investigation, e.g., the details about the status of the Gulf Stream boundaries, the warm- and cold-core rings detected or suspected, etc. The Graphics (Display) Output represents a capability to display information about events in the DDB and inferences made about the expected evolution of events as based on knowledge-base rules in the SDB. Ultimately, the system should also interface directly to image processing algorithms.

II. Mesoscale oceanographic events

The input data for the system is to be a sequence of registered infrared images of the Gulf Stream region of the North Atlantic nearest the U.S. coast (roughly, an area bounded by 50–80°W and 25–45°N). The oceanographic events around which the system is organized are the following:

- landmass boundaries (coastlines);
- warm-core eddies or rings (WCRs);
- cold-core eddies or rings (CCRs);
- Gulf Stream boundaries;
- especially active areas on the Gulf Stream boundaries in which locally rapid changes are occurring.

These five types of event are of primary importance in the description of mesoscale features of the ocean in this North Atlantic region. Figure 1, a hand-drawn plot from NAVEASTOCEANCEN (Norfolk, Virginia), illustrates this environment. An effort has been made to build a knowledge base of contemporary expertise about these events that will be expanded as more details become available in the future.

The knowledge gained from talks at NORDA and from the technical literature consists primarily of expected values/actions describing the location and evolution of events. This knowledge base reflects the fact that in this important and rapidly developing field, much of the

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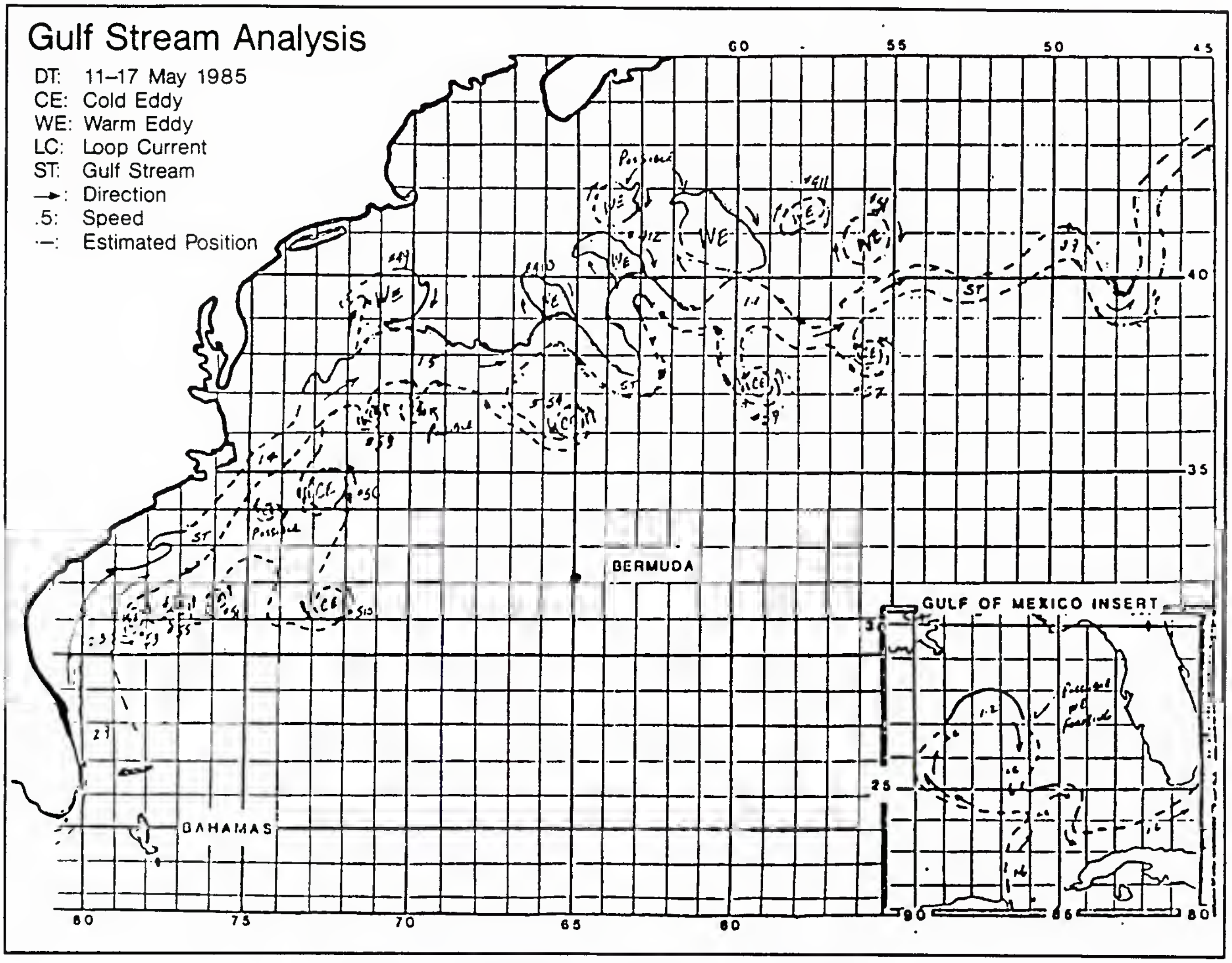

Figure 1. NAVEASTOCEANCEN plot May 1985.

expertise about mesoscale features of the Atlantic is still developing and that complete analytical explanations of these features are not at hand. Expert oceanographers note this situation explicitly in the literature. Concerning the movements of rings, for example,

> Attempts to explain the migration pattern of rings have not been totally successful [15, p. 1094]; and
>
> Further progress is needed . . . before a clear understanding of ring trajectories . . . is obtained [13, p. 32].

Nonetheless, experts agree on the expected aspects of that motion and on many other mesoscale characteristics as well.

A comprehensive summary of the knowledge base is given in the following section. We illustrate some specific examples about events of interest.

Figure 2 shows the formation of a CCR as inferred from NOAA infrared data and expendable bathythermograph data in 1976 [14]. A CCR is formed when cold Slope Water north of the Gulf Stream is enclosed by a major southward meander. A new CCR will have a core 100–300 km in diameter, and its isotherms may be elevated 500–600 m above those of the surrounding Sargasso Sea water. A CCR rotates counter-clockwise. A CCR generally moves south as it breaks away from the Gulf Stream; moves westward at 4–6 cm/sec when free of the Gulf Stream and other influences (other CCRs, storms, etc.); then moves north toward the Gulf Stream and subsequently east during encounters with the Gulf Stream. This looping may recur many times before the CCR finally coalesces with the Gulf Stream. The mean lifetime is somewhat over a year, during which a CCR decays at a slower rate when isolated and drifting southwestward, but at a faster rate when encountering the Gulf Stream. Translational and rotational velocities are increased during these encounters.

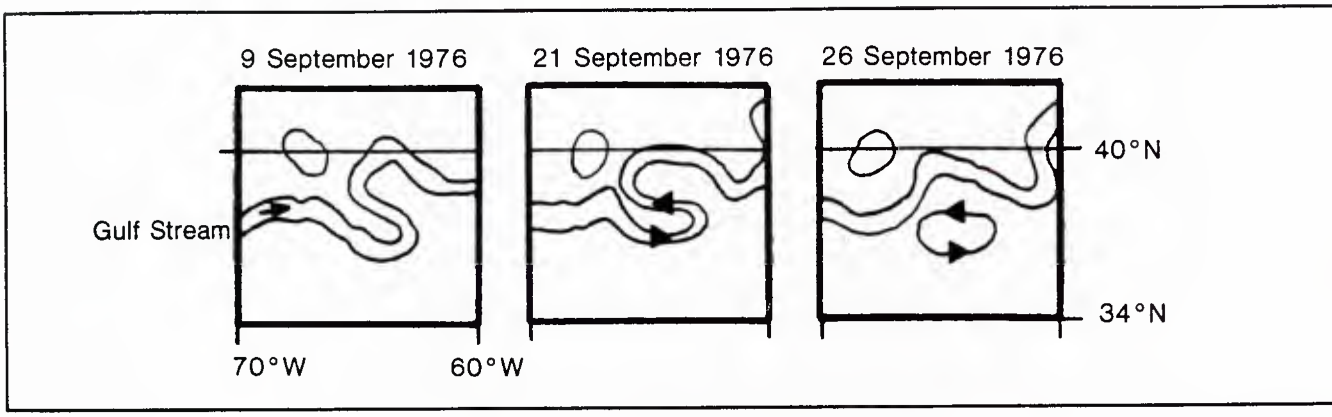

Figure 2. Formation of a CCR (from [14]).

A WCR may be formed by two methods [13]. The first is analogous to that for a CCR, namely, by a major northward Gulf Stream meander in which Sargasso Sea water is enclosed. This method gives rise to the larger WCRs, typically 200–300 km in diameter, usually seen east of Georges Bank. Based on NOAA infrared data in 1982, Figure 3 shows the second way in which a WCR may be created, that is, as a ring of Gulf Stream water itself [16]. This second method forms the smaller WCRs, typically 60–150 km, to the west of the larger ones. Formed either way, a WCR rotates in a clockwise direction. After several months, a WCR eventually coalesces with the Gulf Stream after moving generally west and southwest at an average of about 5 cm/sec, and is constrained by the Gulf Stream to the south and the continental slope to the north. During Gulf Stream encounters, a WCR experiences changes, particularly in translational velocities; its rate of decay is increased as the Gulf Stream absorbs energy and volume from the ring.

The kind of information available about expected characteristics of the Gulf Stream is illustrated in Figures 4 and 5. Figure 4 shows the mean and the extremes of the position of the Gulf Stream found in a study of the ocean front analysis charts generated weekly by the U.S. Naval Oceanographic Office from NOAA infrared data for the two-year period 1975–1977 [4]. Figure 5 shows a periodic seasonal shift of the Gulf Stream mean position between 50°W and 75°W, based on data from 1965–1966 [20]. The Gulf Stream's "small-scale" meanders (up to 150 km phenomenon) appear and disappear on a weekly basis, and the larger meanders vary substantially over a week's time. Statistical properties of Gulf Stream meanders are available [4,19], but details of the short-term evolution of the Gulf Stream in particular need to be expanded in the knowledge base by analyzing real satellite data specifically for that purpose.

III. A summary of knowledge about oceanographic events

The following is a statement in layman's language of knowledge-base information about WCRs, CCRs, and the

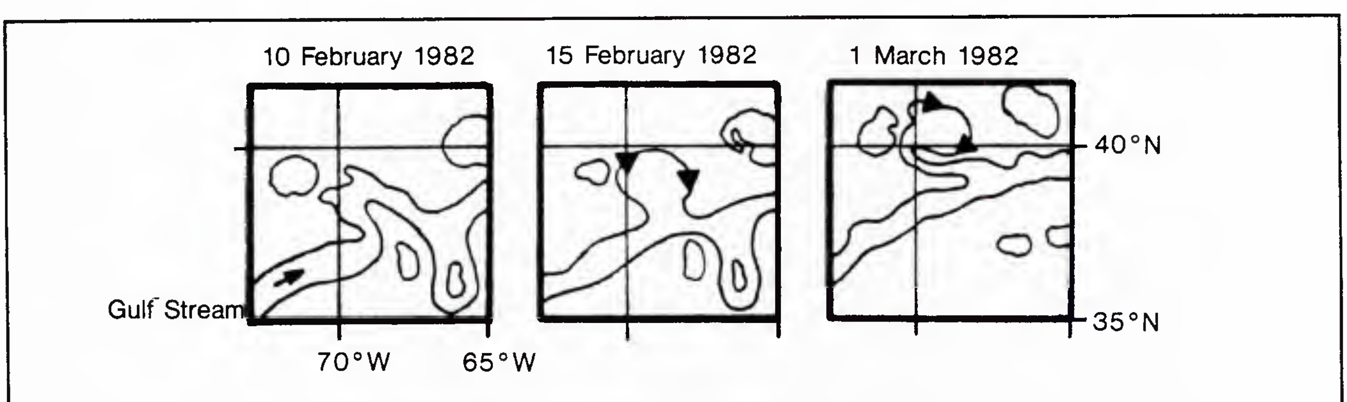

Figure 3. Formation of a WCR (from [16]).

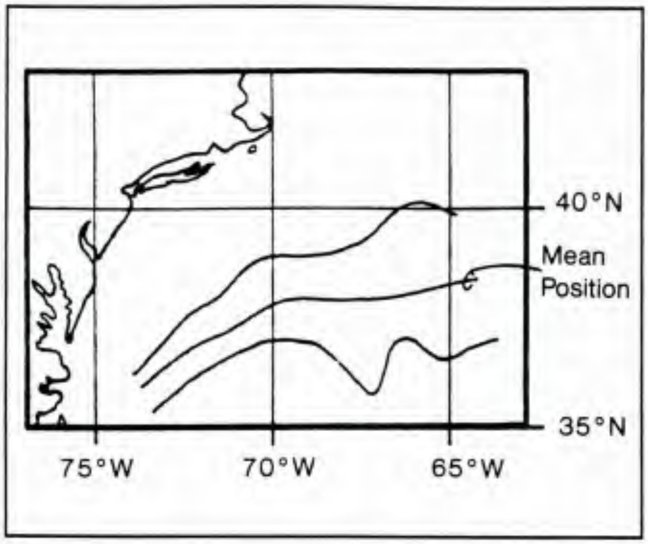

Figure 4. Mean and extreme positions of the Gulf Stream (from [4]).

Gulf Stream obtained from NORDA and from the technical literature in oceanography. Citations indicate at least one published source of the information; "personal communication" from NORDA could also be cited for many items, but this is not done explicitly.

This information is the base of a "world model" for the environment of mesoscale oceanic features detectable in satellite data in the indicated region of the Atlantic. It is important to note that the information represents order-of-magnitude estimates of expected values/actions in most cases. Rules detailing the more subtle and rapidly varying aspects of events must be added as experience with real data is acquired.

Warm-core rings

Formation

1. A WCR is a clockwise-rotating (anticyclonic) eddy formed in the slope water region between the continental shelf and the Gulf Stream [2,12].
2. WCRs have been observed to form only between 60°W and 70°W, but their existence east of 60°W and their general westward movement implies that formation east of 60°W also occurs [13].
3. A WCR can be formed by a major northward meander of the Gulf Stream that encircles Sargasso Sea water. This formation creates a larger WCR that has a diameter of 200–300 km and a core of Sargasso Sea water surrounded by a remnant of Gulf Stream water. This formation generally occurs east of Georges Bank [13].
4. A WCR can be formed by a separation of Gulf Stream water as a bulge associated with a northward meander. This formation creates a smaller WCR that has a diameter of 60–200 km and a core of Gulf Stream water. This formation generally occurs to the west in the active formation region [13].
5. The initial core surface temperature is on the order of 18–20°C and is surrounded by Slope water on the order of 15°C at the surface. A cross section of the isotherms shows inverted bell-shaped curves, which flatten as the WCR ages [12].

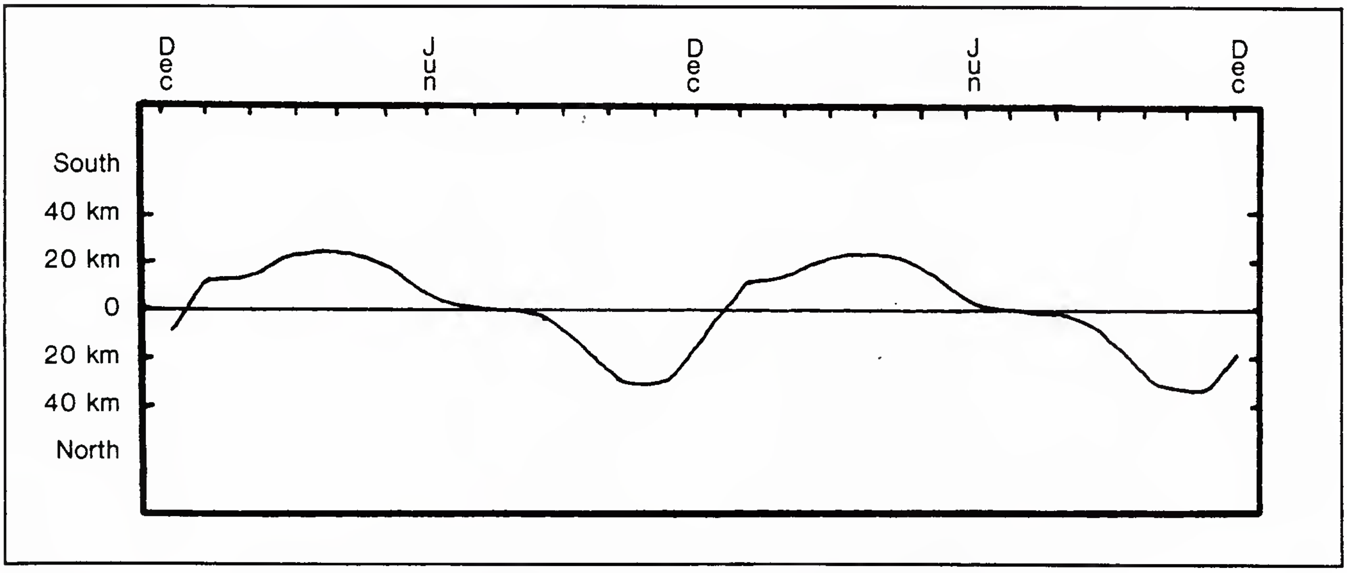

Figure 5. Seasonal variation of mean position of the Gulf Stream (from [20]).

6. A WCR's near-surface core rotational velocity increases with distance from the center and might reach a peak greater than 50 cm/sec at a radius of 30–60 km, then falls off toward the outer limits of the ring [12].

7. About three or four WCRs typically coexist at a time [4,13].

Expected movement

1. A WCR moves generally southwest at 3–8 cm/sec. and is constrained by the Gulf Stream and the continental slope; this speed is on the order of the mean flow on that side of the Gulf Stream [13].

2. A WCR formed east of 65°W generally propagates westward to strike the Scotian Shelf or Georges Bank, then southwestward along the continental shelf.

3. A WCR formed between 70°W and 65°W tends to make quick contact with the continental shelf, then to move toward Cape Hatteras [4].

4. WCR movement is influenced by the ocean-bottom topology [2,4]. A WCR tends to follow a bottom topology line, but the following have been observed:

- translation speed increases from 3–4 cm/sec to 7–8 cm/sec upon entering Hudson Canyon and moving across bottom topology lines through the Canyon [2];
- reduction in ring diameter from about 120 km to 90 km in transit through the Hudson Canyon [4];
- maintenance of 7–8 cm/sec translation but return to southwestward movement on leaving Hudson Canyon [2];
- reduction to 2–3 cm/sec average translation when reaching Cape Hatteras area [2].

5. Encounters with the Gulf Stream may temporarily increase translation speed up to three times nominal for a newer WCR (e.g., 7–8 cm/sec boosted to 20+ cm/sec) and up to 25 times for an older WCR toward the end of its life in the Cape Hatteras area (e.g., 2–3 cm/sec boosted to 50 cm/sec) [2].

Evolution and decay

1. A WCR ultimately coalesces with the Gulf Stream; the mean lifetime is about half a year [12,13].

2. Most WCRs coalesce with the Gulf Stream in the area of Cape Hatteras; some are permanently captured by Gulf Stream meanders south of Georges Bank or New England before arrival at Cape Hatteras [2].

3. A WCR's potential energy is 3–4 times its kinetic energy over much of its life [12].

4. The loss of potential energy of an isolated WCR implies a half-life of 1.2–1.5 years, which is comparable to an isolated CCR [12].

5. The typical rate of decrease of potential energy of an isolated WCR is comparable to that of an isolated CCR: 95 MW [12].

6. The typical rate of decrease of volume of an isolated WCR is on the order of 0.04*(10**6) m/sec^3 [12].

7. Encounters with the Gulf Stream tend to increase as a WCR moves toward Cape Hatteras [4,12], becoming as frequent as every 3–4 weeks toward the end of its life [2].

8. In an encounter, the Gulf Stream typically absorbs WCR energy and volume. Energy and volume may decrease at rates of 900 MW and 1.4*(10**6) m/sec^3, respectively [12].

9. Encounters with the Gulf Stream tend to cause an inward shift of the location of the maximum rotational velocity on the order of 10 km toward the ring center [12], and to cause a reduction in core diameter (110 km down to 70 km has been observed [2]); but the rotational velocity peak tends to be preserved over much of the lifetime of a WCR [12] (this is consistent with conservation of potential vorticity [12]).

10. The core average temperature may be changed by entrainment of other water. Streamers (''fingers'') of colder Slope water or of warmer Gulf Stream water may penetrate the core and cause 3–6°C temperature adjustments [2].

11. A WCR may be overwashed with Gulf Stream water and be temporarily lost to infrared [4].

12. A WCR may have associated vortices (smaller, isolated components of diameter on the order of 30 km with a closed circulation of their own), possibly created as it moves toward shallower topology (toward continental shelf) and existing for 1–2 weeks [12]. These cyclonic vortices often appear to the northeast of a WCR as it encounters canyons or enters the area of Cape Hatteras and are invected clockwise around the ring [2].

Cold-core rings

Formation

1. A CCR is a counter-clockwise (cyclonic) rotating eddy formed south of the Gulf Stream in the Sargasso Sea [13,15].

2. A CCR forms from 70°W eastward; most have been observed in the region 60–70°W [13].

3. The strongest observed CCRs have been north and northwest of Bermuda [13], that is, north and northwest of about 65°W, 32°N.

4. A CCR is formed by a southward Gulf Stream meander and has a cold Slope Water core encircled by a remnant of Gulf Stream water. The core is in near-solid body rotation, is often elliptical when new, but becomes nearly circular [13].

5. The Gulf Stream remnant is approximately 500 km long by 100 km wide by 2 km deep [13].

6. A new core is typically 200–300 km in diameter at 10–16°C surface temperature, surrounded by Sargasso Sea water that may exceed 20°C at the surface [13,15]. A cross section of the isotherms shows bell-shaped curves that flatten as the CCR ages [15].

7. A new CCR may have its colder isotherms raised 500–600 m above those of surrounding Sargasso Sea water [15].

8. A CCR's near-surface rotational speed may be up to 150 cm/sec [15]; the speed increases with distance from the center to a maximum at 30–60 km radius, then falls off toward the outer limits of the ring [13].

9. A new CCR appears to extend to the sea floor [15].

10. About 10 CCRs typically coexist at a time west of 55°W [13].

Expected movement

1. A CCR moves south from the Gulf Stream; then west when free of the Gulf Stream; then north to reencounter the Gulf Stream; then east with the Gulf Stream until it breaks away southward again or coalesces with the Gulf Stream [13,15].

2. A CCR moves in a clockwise loop, which has a period of about 2–3 months and a diameter of 100–200 km north and west of Bermuda [13,15].

3. A CCR drifts southwestward during its life in an apparent "channel" located 200 miles offshore of the Gulf Stream axis between 28°N and 36°N [13].

4. A CCR's translation speed averages 5–10 cm/sec while free of the Gulf Stream and other influences (other CCRs, etc.); this speed is comparable to the mean flow on that side of the Gulf Stream [13].

5. During Gulf Stream encounters, the translation speed may be increased more than five times nominal (e.g., from 5 to 25+ cm/sec) [15].

Evolution and decay

1. A CCR ultimately coalesces with the Gulf Stream; the mean lifetime is from 1.2 to 1.5 years [15]. There is no evidence of any other fate (e.g., terminal decay while drifting southward in the Sargasso Sea has never been observed) [13,15].

2. In coalescence, a relatively intense CCR may attach to the Gulf Stream; the Gulf Stream flows around the CCR to produce an open meander in which CCR water joins cold Slope water. This meander may reform a CCR [15], but the mean number of recycled CCRs is unknown [13].

3. In coalescence, a relatively weak CCR may attach to and be invected downstream by the Gulf Stream [15].

4. A CCR's potential energy is 2–3 times its kinetic energy over much of its life [13].

5. The loss of potential energy by an isolated CCR is not necessarily exponential. As for an isolated WCR, there is an implied a half-life of 1.2–1.5 years [13,15].

6. The typical rate of decrease in potential energy of an isolated CCR is comparable to that of an isolated WCR: 95 MW [12].

7. In an encounter with the Gulf Stream, significant amounts of water and energy may be exchanged. If the CCR does not coalesce with the Gulf Stream in the encounter, the peak core rotation rate increases and may double in frequency, but at a smaller radius from the center as the CCR is "spun up" by the Gulf Stream [13,15] (this is consistent with conservation of potential vorticity [13]). The core temperature may be raised 2–3°C [14]. An estimated rate of injection of Gulf Stream water into the CCR in a major encounter is 10**6 m/sec^3 [14].

8. If the figures are comparable to WCRs, the rate of decrease in potential energy of a CCR in a major Gulf Stream encounter may be as high as 900 MW [12].

Other ring characteristics and special cases

1. Typically, fewer WCRs than CCRs exist at a time [13]. WCRs have smaller average size [13] and, shorter average lifetime [12] than CCRs.

2. WCRs and CCRs play an important, but incompletely understood, role in the overall Gulf Stream transport and its variations [13].

3. A large, isolated CCR has been observed to split spontaneously into two smaller rings several months after formation. The double ring was large and elliptical before the splitting, and the major axis about 500 km at temperatures colder than 15°C extended over approximately 67–62°W, 35.5–37.5°N. After the split, the smaller CCR moved rapidly eastward and coalesced with the Gulf Stream; the larger CCR moved in a large clockwise loop, attached to the Gulf Stream, and was recycled as a smaller CCR that coalesced with the Gulf Stream [14].

The Gulf Stream

1. The mean width of the Gulf Stream is approximately 100 km in regions away from rings [14].

2. The seasonal shift in the mean position of the Gulf Stream between 50°W and 75°W, based on 1965–1966 data, appears in Figure 4 [19].

3. The mean and extreme positions of the Gulf Stream for 1975–1977 appear in Figure 3 [4].

4. The mean position shifts relative to the U.S. coast over a period of years. For a two-year period, a shift toward the coast has been observed to range from 35 km near Cape Hatteras to 60 km south of New England. Otherwise, the statistics of the Gulf Stream have seemed essentially stationary [4].

5. The rms amplitude of the Gulf Stream variability increases from 15 to 80 km in the first 1.6 km downstream from Cape Hatteras [4]. In the region from 100 to 200 km downstream from Cape Hatteras (about 73–75°W), the variance doubles in each 50 km step as the rms amplitude increases from 15 to 20 to 30 km; near 65°W, the rms amplitude reaches 80 km in a region where the envelope of the variations increases to 200–300 km, the variance doubles in about 400 km, and the amplitude itself can be comparable to the wavelength [19].

6. The small-scale Gulf Stream meanders, on the order of 150 km, appear and vanish on a weekly basis; their amplitude tends to be an order of magnitude smaller than that of the large-scale events [4].

7. A spectral peak in wavelength of the dominant, large-scale Gulf Stream meanders was about 320 km and had periods of 7–8 weeks. There were wavelengths between 220 km and 600 km and two dominant period bands: 6–10 weeks and 17–52 weeks. Propagation was downstream at about 6 cm/sec, decreasing in wavelength and increasing in amplitude [4].

8. Gulf Stream meander amplitude has been observed to increase following a WCR encounter; this can aid the formation of additional rings [2].

9. A semi-permanent "ring-meander" overlies the New England seamounts; a CCR appears at times to be forming here, but often remains trapped near the seamounts. It either does not completely separate from, or quickly coalesce with, the Gulf Stream [13].

10. The mean Gulf Stream transport is estimated as 30*(10**6) m/sec^3 off Miami, increases to 150*(10**6) m/sec^3 north of Bermuda, and then decreases in the flow toward the Grand Banks [13].

IV. The knowledge base as a model

A critical component in an expert system to aid oceanographic image analysts is a model of mesoscale events. A "model" here essentially refers to the overall way in which the qualitative/quantitative knowledge-base rules are organized and used in the system's computations. For example, if more than one knowledge-base rule is found to apply to a given situation, the model assigns execution priorities to the applicable rules. (This concept of modeling is in contrast with numerical modeling of physical phenomena based on deeper theoretical studies or detailed analytical simulations.) The high-level function of the model in this specific knowledge-based system is to guide the tracking of mesoscale events and the forecasting of events' evolution over the short term (periods of days or weeks). It is intended that the ultimate system be capable of tracking events and predicting their short-term evolution with greatly reduced human interaction; thus, the test of the model ultimately will be how well the system performs these two tasks.

A fundamental requirement of the model is that it provide a coherent, knowledge-based interpretation for the sequence of observations. Thus, the model must be able to incorporate partially obscured observations and to accommodate observed behavior that differs from the expected behavior predicted. This requirement implies an ordering on rules concerning the evolution of an event: rate-of-change constraints are first, observations within those constraints are second, and predictions based on expected values are last.

To enhance understanding and forecasting of events, the system should be able to use a history of observed/predicted events to provide a dynamic display (with explanations) over a time period. Since evolution is a combination of deterministic and random processes, in displaying its predictions the system should indicate a coarse measure of the probability of correctness of predicted events; the model will have to provide that measure.

A pilot implementation has been based on an embryonic model of the expected movement and evolution of WCRs and CCRs. Using information in the knowledge base summarized in Section III, the pilot implementation enumerates expected actions of some isolated events and the events' interactions via rules for different regions of the ocean. In this preliminary work, no provision has been made for updating via additional observations or for displaying probabilities of correctness in evolution; these updates will require considerable effort in the next phase of this project.

In future work, the model should be specified in files separately from the other driving programs. This organization follows the design principle that "knowledge" and "inference engine" should be distinct. It also has the practical advantage that the model can be adjusted/corrected without affecting other parts of the system.

Finally, to facilitate interaction with users and explanations in users' common terms, the model should be aimed at the descriptive level used by oceanographers to characterize mesoscale events, e.g., by using oceanographic regions in which isolated events behave in a uniform manner (with the expected characteristics of events in the region) and in which close events interact with a behavior described by position-sensitive rules.

V. A brief comparison of computer languages

The expert system could be implemented in any of a number of languages, including LISP, PROLOG, OPS5, OPS83, or such procedural languages as C or PASCAL. Concerning these possibilities, it should be noted that programming an expert system differs from conventional programming in that rule-based processing is performed; that is, the most successful contemporary method of endowing a program with an ''expert-like'' ability to make a (potentially complex) sequence of decisions is to use non-procedural, rule-based programming techniques and a knowledge base of expertise as a ''model.'' In rule-based programming for expert systems, the concept variously called a production, an if-then rule, or a logical implication generically has the form LHS$\longrightarrow$RHS and has the meaning that ''if the lefthandside LHS is TRUE, then the rule is satisfied and may be executed or 'fired' to yield a righthandside RHS also TRUE.'' Different programming languages use entirely different syntax for defining rules and different strategies for firing them.

Some expert systems operate on a minimum of actual input/output data, with inputs often being entered by a user at a keyboard as answers to questions; this kind of expert system generally uses rule-based computation and little, if any, conventional procedural programming. By contrast, the oceanographic system under development here will include input from large image datafiles and will be required to interface to display devices to provide some of its output; ultimately, it should also manipulate image processing algorithms. Thus, it is appropriate to view its rule-based component as one part of the total programming of a system in which substantial requirements for conventional procedural computations also exist.

LISP

LISP dates from the 1960s as a list processing language in which all data are represented as symbolic expressions. Nesting of expressions is interpreted as defining a binary tree. Built-in functions return subtrees as values, test data for equality, and so on. (The concepts of trees are fundamental to the representation of data in LISP and to the notions of symbolic processing in general.) There is a rule construct with the form [p1$\longrightarrow$e1, p2$\longrightarrow$e2, . . . , pm$\longrightarrow$em], where pi$\longrightarrow$ei represents ''predicate pi implies expression ei''; the value returned by this operation is the value of ei for the leftmost TRUE pi, and is undefined if all pi's are FALSE.

LISP may be used as the base language in which to implement an expert system ''shell'' that provides a toolkit of functions, procedures, structures, etc., and is considered useful in constructing or in running an expert system. Such shells are commercially available.

PROLOG

PROLOG is about 10 years old and reflects an interest in programming in logic in that its statements are interpreted as sentences of a logic. Roughly speaking, as a PROLOG program runs, there is at any time a current data base of TRUE statements (the knowledge base) in which each statement is taken to be a predicate in which unbound variables may appear. Some of these predicates are implications, as, for example, P(x)$\longrightarrow$Q(x) in which the TRUTH of P(x) implies the TRUTH of Q(x). (Recall the definition of implication in Boolean logic: P(x)$\longrightarrow$Q(x) means ''if P(x) is TRUE, then Q(x) is TRUE; but if P(x) is FALSE, Q(x) may be TRUE or FALSE.'')

Unless constrained otherwise by explicit program structure, PROLOG carries out an exhaustive search in the knowledge base. During the search it is constantly seeking to establish the TRUTH of various (chains of) propositions by binding variables in predicates to values for which TRUE entries can be found in the knowledge base. The knowledge base may be modified by propositions in the program that either ASSERT new entries (say, using data supplied by the user) or RETRACT existing ones.

As with LISP, an expert system ''shell'' may be developed in PROLOG to facilitate the knowledge-base construction, the user interface, and the other requirements of a specific application.

OPS

The OPS languages were developed during the 1970s to support programming directly in productions or if-then rules. OPS5, which does not support procedural programming, has been widely used for expert systems. For example, a system to process aerial imagery has its rule-based component implemented in OPS5 [11].

Data in OPS5 are vectors of attributes with their values, e.g., a WCR with reference name WCR6, a diameter of 110 km, and a velocity of 4 cm/sec might be an instance of a vector such as

(Warm-Core Ring Name WCR6 Diameter 110
Velocity 4 . . .).

Rules have the form [antecedent]⟶[consequent]. A rule is satisfied if the current data base entries make the antecedent TRUE. In a step in the computation, all satisfied rules are found; then one is selected by a control strategy, and its consequent actions are performed. Those actions may result in a changed data base that satisfies a new set of rules, and the process continues. New data will launch a new rule-based computation.

OPS83

OPS83 is a 1980's expert system programming language offering facilities for rule-based programming and for procedural programming as well. Thus, rule-based computation (as in OPS5 and PROLOG) and procedural computation (as in PASCAL and C) are possible in the same language. Linking to external procedures written in other languages (FORTRAN, C, etc.) is also straightforward.

The procedural statements define a recursive, pointer-based language. Data for the rule-based computations resides in "working memory" and is manipulated by MAKE, MODIFY, and REMOVE commands. For example, a record structure for the type WCR could be declared with fields for the parameters of a warm-core ring; then a new WCR can be entered into current working memory by using MAKE to create a new instance of the type, can be updated by using MODIFY as evolution occurs, and can be REMOVEd from working memory upon coalescence with the Gulf Stream.

A rule is declared with a name, an LHS, and an RHS in the form NAME:LHS⟶RHS. The RHS is the body of a procedure. The LHS specifies patterns that must be satisfied by the current working memory to activate the rule. "Match the patterns" is evaluated as a Boolean value for each rule, and conflicts among all satisfied rules are resolved by a control strategy whereby the actual rule to execute next is selected. The control strategy is written as OPS83 procedures.

Procedural languages

We note finally that rule-based computation can be implemented in full procedural languages, i.e., PASCAL and C, via user-defined procedures and structures that essentially create a "rule language." To define and implement an adequate, robust language for serious rule-based programming is a major task in software development.

VI. Bibliography

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